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Kenny Hey Tow,[1,2,*] Yohann Léguillon,[1,2] Pascal Besnard,[1,2] Laurent Brilland,[3] Johann Troles,[1,4] Perrine Toupin,[1,4] David Méchin,[3] Denis Trégoat,[3] and Stéphanie Molin[5]

[1]UEB, Université Européenne de Bretagne, Université de Rennes 1, Rennes, France

[2]CNRS UMR 6082 FOTON, Enssat, 6 rue de Kerampont, BP 80518, 22305 Lannion, France

[3]PERFOS, 11 rue Louis de Broglie, 22300 Lannion, France

[4]Equipe Verres et Céramiques, CNRS, UMR 6226 SCR, Campus de Beaulieu, 35042 Rennes, France

[5]THALES Research and Technology, 1, avenue Augustin Fresnel, 91767 Palaiseau, France

*Corresponding author: heytow@enssat.fr

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Relative intensity noise and frequency noise have been measured for the first time for a single-frequency Brillouin chalcogenide $As_{38}Se_{62}$ fiber laser. This is also the first demonstration of a compact suspended-core fiber Brillouin laser, which exhibits a low threshold power of 22 mW and a slope efficiency of 26% for nonresonant pumping.

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Brillouin fiber lasers (BFLs) have been attracting a lot of interest lately due to their very narrow linewidth [1] and very low relative intensity noise (RIN) and frequency noise [2–4], making them excellent coherent laser sources. Recently, a BFL made of 4.9 m long bulk As_2Se_3 (AsSe) chalcogenide fiber, which has a Brillouin gain coefficient g_B more than 2 orders of magnitude higher than that of silica-based fibers, has been reported [5]. This laser had a threshold of 35 mW for nonresonant pumping and an efficiency of 38% [6]. One way to reduce the threshold of the laser and to make more compact lasers is to combine a microstructured fiber (MOF) to the chalcogenide glass, which reduces the effective area of the fiber. To our knowledge, no BFL based on chalcogenide MOFs has yet been mentioned in the literature, although experimental [7] and modal characterization (through theoretical simulations) of stimulated Brillouin scattering have been reported [8]. The purpose of this Letter is twofold: first to demonstrate the possibility of making compact BFLs made of AsSe chalcogenide MOFs with low threshold power and excellent spectral purity; and second, to report the noise performances in terms of intensity and frequency noise of a BFL made of chalcogenide MOF.

The AsSe MOF [inset of Fig. 1] used in this Letter is prepared by using a casting method [9]. The chalcogenide glass is heated around 500 °C and flowed into a silica mold that contains aligned silica capillaries. This method enables the realization of low loss fiber. During the drawing step, the hole sizes are adjusted by applying a positive pressure in the preform holes [10]. The external diameter of the AsSe suspended-core fiber is 240 μm and the core diameter is 4 μm. The mode effective area was estimated to be around 8 μm^2 and the fiber losses were found to be $\alpha = 1$ dB/m at 1.55 μm. An experimental characterization of Brillouin scattering in the AsSe MOF was done using the setup and method detailed by *Abedin* [6]. The stimulated Brillouin scattering threshold power is defined as the pump power for which the power of the Stokes component equals that of the transmitted one [7]. A g_B of 5.5×10^{-9} m/W, a Brillouin frequency shift of around 7.95 GHz, and a Brillouin gain linewidth of 14.2 MHz were measured using a heterodyne detection [11] for the AsSe suspended-core chalcogenide fiber. This value is slightly less than the g_B measured by *Abedin* and can be explained by the presence of the air holes in the fiber [11,12].

A BFL was made using a 3 m long AsSe suspended-core fiber. The configuration of the BFL is shown in Fig. 1. A commercial distributed feedback (DFB) fiber laser (Koheras AdjustiK System) from NKT Photonics, having a linewidth of around 1 kHz and emitting at around 1550 nm, was used as pump laser (PL). This pump signal was amplified up to 23 dBm thanks to an erbium doped fiber amplifier and injected into the AsSe fiber via the port 2 of an optical circulator using a high numerical aperture fiber with a mode field diameter and a numerical aperture measured to be respectively 3.16 μm and 0.35. The output of the BFL was extracted from a 10% fiber coupler while the remaining 90% was fed back into the cavity. This particular design of the BFL cavity with a circulator allows free propagation of the Stokes waves,

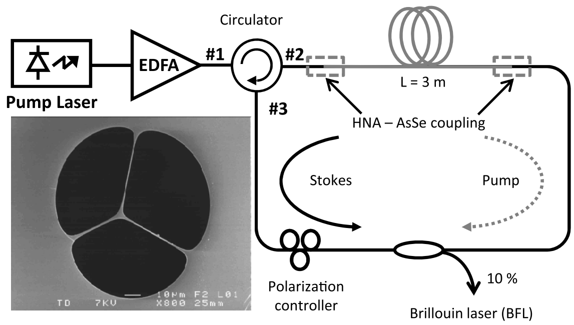

Fig. 1. Configuration of the ring cavity BFL. Inset shows the transverse section of the AsSe MOF.

which perform multiple round-trips, while the pump wave interacts only over a single loop. The main advantage of this cavity over a conventional ring-resonator cavity [13] is that there are no resonant conditions for the pump, and thus, no need to servo-lock it with a feedback loop. Our fiber being not polarization-maintained, a polarization controller was inserted inside the cavity to ensure that the polarization of the pump is kept parallel to that of the Stokes wave to yield maximum Brillouin gain. The laser cavity consisted of 3 m of AsSe fiber and 5 m of single mode fiber, resulting in a total optical cavity length of 15.7 m ($5 \times 1.45 + 3 \times 2.81$). This corresponds to a free spectral range (FSR) of 19 MHz, which is more than the measured Brillouin gain bandwidth (14.2 MHz), ensuring that only one single longitudinal mode is oscillating inside the cavity. The total round-trip linear losses, which includes 3 dB due to transmission losses in the chalcogenide fiber, 5 dB of coupling losses, and 2.5 dB across the optical components in the ring cavity, is estimated to be around 10.5 dB.

Figure 2 shows the Stokes output power as a function of the pump power. As expected, the Stokes output power is proportional to the pump power. The AsSe BFL exhibits a low threshold of 22 mW for single-pass pumping and converts the pump to the first-order Stokes wave with an efficiency of 26%. For a complete comparative study, the same experiment was performed using a 20 m long classical fused silica single mode fiber (SMF-28) as Brillouin gain medium to obtain a single-frequency SMF-28 BFL. The total cavity length is then 25 m. This corresponds to a FSR of 8.28 MHz, which is slightly less than the Brillouin gain bandwidth in silica (≈10 MHz). The total round-trip loss is estimated to be only 3 dB. In this case, a higher threshold power of 110 mW is measured.

The AsSe BFL was also characterized in terms of intensity and frequency noise. Figure 3 shows the RIN of the AsSe BFL obtained using the method described by Cox *et al.* [14] with a noise measurement limited to 10 MHz due to the bandwidth of our low-noise transimpedance amplifier. The RIN of the PL as well as the SMF-28 BFL were also included on the same plot for comparison. The RIN of the PL presents a classical behavior: a noise floor for low frequencies followed by a peak due to the relaxation oscillation frequency (ROF) at 150 kHz and by a decrease at higher frequencies. This ROF peak is trans-

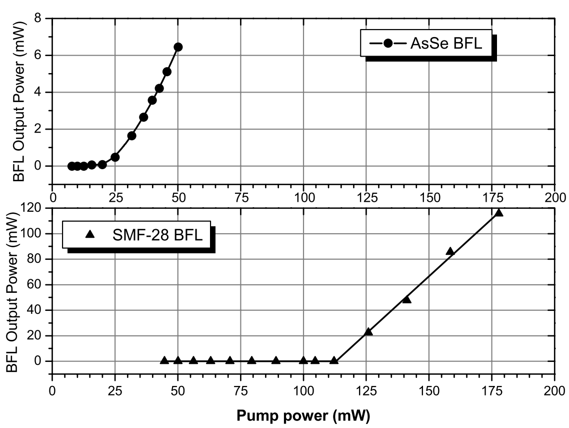

Fig. 2. BFL output power as a function of pump power.

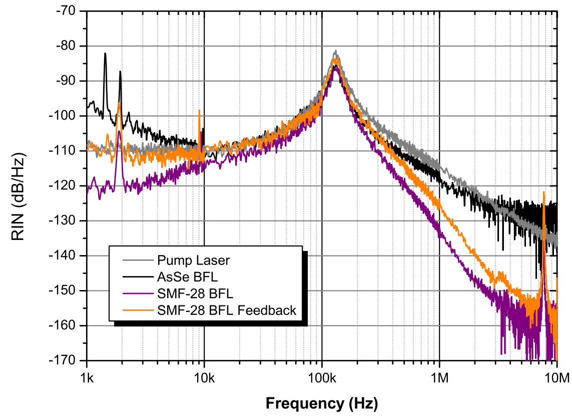

Fig. 3. (Color online) RIN spectra of the BFLs.

ferred to both the AsSe BFL and the SMF-28 BFL with a noise reduction of about 5 dB. An intensity noise reduction is observed for the SMF-28 BFL. The intensity peak at 8 MHz comes from a beating between the laser signal and another longitunidal mode. For the AsSe BFL, although a RIN reduction is observed around the ROF, an excess of intensity noise is measured for frequencies below 10 kHz and above 3 MHz. This increase in intensity noise can partly be explained by the relatively high reinjection rate caused by the Fresnel-reflected pump power inside the ring cavity, which is due to the large discrepancy between the refractive index of the chalcogenide fiber ($n \approx 2.81$ at a wavelength of 1550 nm) and that of air. To confirm this assumption, part of the pump signal was reinjected inside the SMF-28 BFL using an optical coupler to have approximately the same amount of pump signal in the ring cavity circulating in the "Stokes" direction as in the case of the AsSe BFL. This has resulted in an increase of the RIN (orange curve), thus suggesting that the pump feedback in the AsSe BFL brings excess intensity noise. Another reason for the relatively high RIN in the AsSe BFL is the fact that the polarization state of the generated Stokes wave in our suspended-core chalcogenide fiber was largely dependent on ambient temperature. Indeed, we observe that with increased pump power it becomes more and more difficult to obtain a stable output power of the AsSe BFL. Finally, it is also worth noting that both BFLs are very sensitive to environmental noise as illustrated by the multiple noise peaks in the BFLs spectra for low frequencies (10^3 Hz–10^4 Hz).

The frequency noise of the AsSe BFL [Fig. 4] was also measured with an unbalanced Mach-Zehnder interferometer. A delay line length less than the coherence length of the laser was used ($L_d = 338$ m). The system functions in coherent mode and the fluctuations of the frequency of the laser were measured by a signal source analyzer (RS FSUP8). The frequency noise spectra of the PL and the SMF-28 BFL were also added on the same plot. As mentioned earlier, the AsSe BFL is very sensitive to environmental noise; this results in an important frequency noise contribution for frequencies below 5 kHz. This is, however, not the case for the commercial DFB fiber laser used as PL since it is properly packaged making it insensible to thermal and acoustic variations. However, for frequencies above 5 kHz, around 6 dB frequency noise reduction compared to the PL is observed [4]. It is

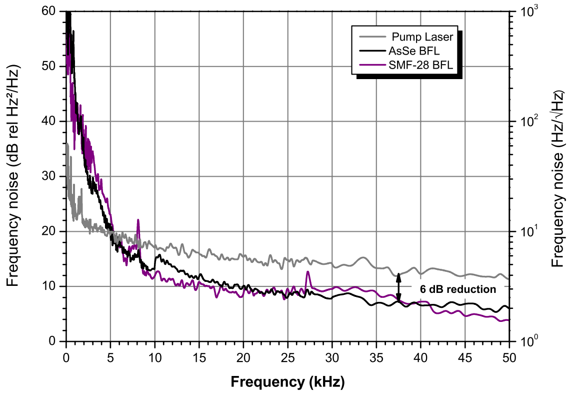

Fig. 4. (Color online) Frequency noise spectra of the BFLs.

interesting to note the same behavior for the SMF-28 BFL as well, thus suggesting that the use of the suspended-core chalcogenide fiber does not bring any frequency noise penalty.

A self-heterodyne technique [15] consisting of an unbalanced Mach–Zehnder interferometer with a 50 km optical fiber delay line (corresponding to a resolution of 4 kHz) was used to measure the spectral linewidth of the AsSe BFL. However the heterodyne beat signal could not be decorrelated for the fiber length delay used, implying that the laser linewidth is less than 4 kHz. An estimated root mean square laser linewidth, $\Delta\nu_{\mathrm{rms}}$, of 1.8 kHz is obtained using the equation $\Delta\nu_{\mathrm{rms}} = \sqrt{\int_0^\infty S_{\Delta\nu}(f)\mathrm{d}f}$, where $S_{\Delta\nu}(f)$ is the frequency noise power density measured in $\mathrm{Hz}^2/\mathrm{Hz}$ [16]. By considering that the frequency noise stays constant for frequencies above 35 kHz ($\nu_{\mathrm{noise}} = 3\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$), we also estimated a spectral linewidth of 57 Hz due to white noise.

To conclude, a BFL made of suspended-core AsSe chalcogenide fiber is demonstrated, for the first time to our knowledge. Using only a 3 m long AsSe MOF, we achieved threshold for single-frequency Brillouin lasing with a pump power of about 22 mW with an efficiency of 26% and a measured linewidth to be below 4 kHz, which is the limit of resolution of our measure. A RIN reduction of 5 dB around the ROF peak and a frequency noise reduction of about 6 dB as compared to the pump laser noise was measured for our chalcogenide BFL for frequencies above 5 kHz. The suspended-core AsSe chalcogenide fiber is a promising Brillouin gain medium since BFLs made of these fibers and operating at a single frequency are compact, exhibit a low threshold, and have very good noise characteristics. BFLs with a threshold power of the order of the milliwatt can be for single-pass pumping, and even at submilliwatt threshold power for resonant pumping, provided a Pound-Drever-Hall frequency-locking technique is used [17], can be achieved by the use of reported AsSe MOFs with smaller effective area and equivalent linear losses (1.15 $\mu\mathrm{m}^2$ and 0.9 dB/m) [18].

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